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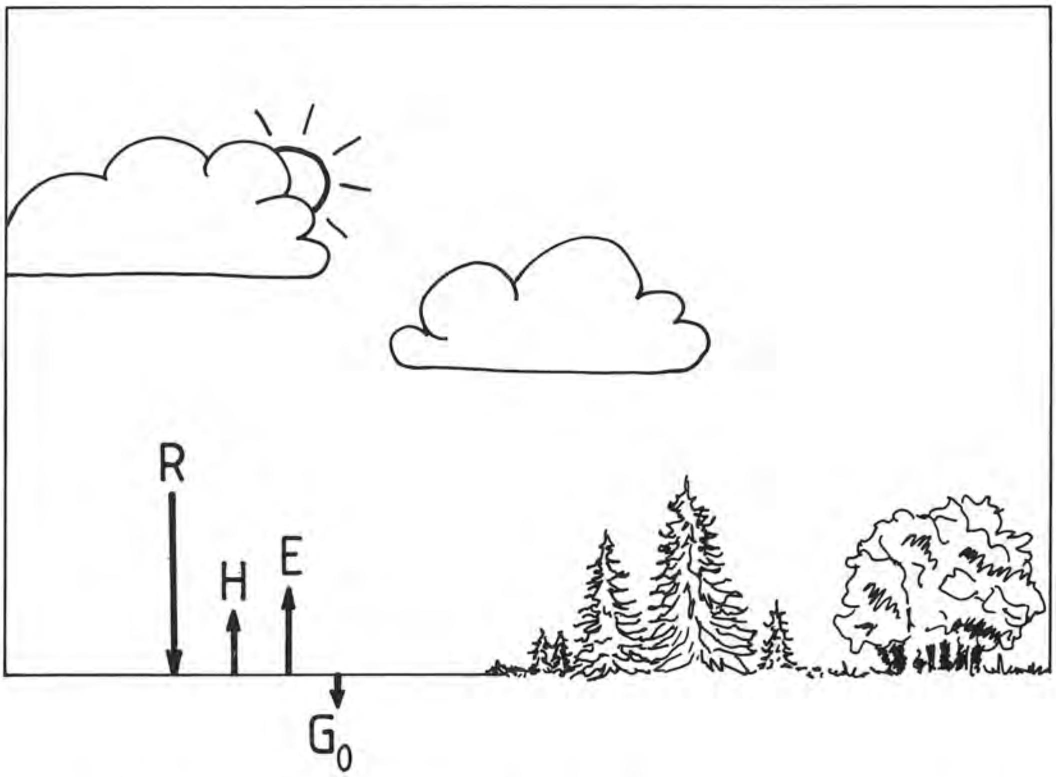

AN ENERGY BALANCE MODEL FOR PREDICTION OF SURFACE TEMPERATURES

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An energy balance model for prediction of surface temperatures.

Abstract

From the winter season 1988/89 and onwards an energy balance model has been used to estimate surface temperatures within a weather service system for the road authorities in "Östergötlands" and "Göteborg-Bohus län" in Sweden. It is based on a simplified form of the energy balance equation at the surface and a numerical model with ten layers in the ground or road. In the road service system manually given forecasts of clouds and wind are used as input into the model. The initial values of surface temperatures are obtained on-line from the road stations involved. Forecasts of surface temperatures have been made for up to five hours and give significantly better results than e.g. perstistency or linear trend forecasts.

The model has also been generalized to run directly on model output clouds an winds and to give forecasts for a large area. As starting values we then use screen temperatures analysed in a grid net with a resolution of about 20 km covering Scandinavia. Initial surface temperatures are obtained through extrapolation to the ground. Through a relaxation formula forecasted surface temperatures are then transformed back to screen level. The temperature forecasts obtained in this way seem to be much better than the LAM-model gives where the daily amplitude is too small.

This latter model is henceforth called the objective system while the former is called the road service system. The two systems have large parts in common. Differing parts are indicated in section headings ant text.

Key words
Energy balance
Surface temperature
Road climate

Supplementary notes

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THE ENERGY BALANCE AT THE SURFACE - BOTH SYSTEMS

The wellknown energy balance equation for a surface can be written

$$G_0=R-H-E$$

where G_0 is the heat flux into the ground, R is the net downward radiation, H is the turbulent upward flux of sensible heat and E is the upward flux of latent heat. In this application we have to estimate G_0 because it is the heat flux into the ground that drives the temperature changes in the ground. G_0 is often substantially smaller then the other terms.

To estimate the net radiation we have used empirical formulae derived from an extensive danish data set (Nielsen et al, 1981). In these equations the net radiation is parameterized as a function of solar height, cloud amount, cloud height, wind speed and ground temperature. An alternative way using the four componenents of the net radiation may be better but requires a careful handling of the downward longwave radiation which nearly balances the upward long-wave radiation. In the corresponding model used in the United Kingdom (Rayer, 1987; Thomes, 1989) the net radiation is obtained through summing of the four radiation components.

The daytime formula for net radiation is summarized by Fig. 1 adopted from Nielsen et al (1981). Note that if the clouds are medium and high the amounts are reduced and transformed into new 'effective' amounts. Wind and ground temperatures enters only in the nighttime equations.

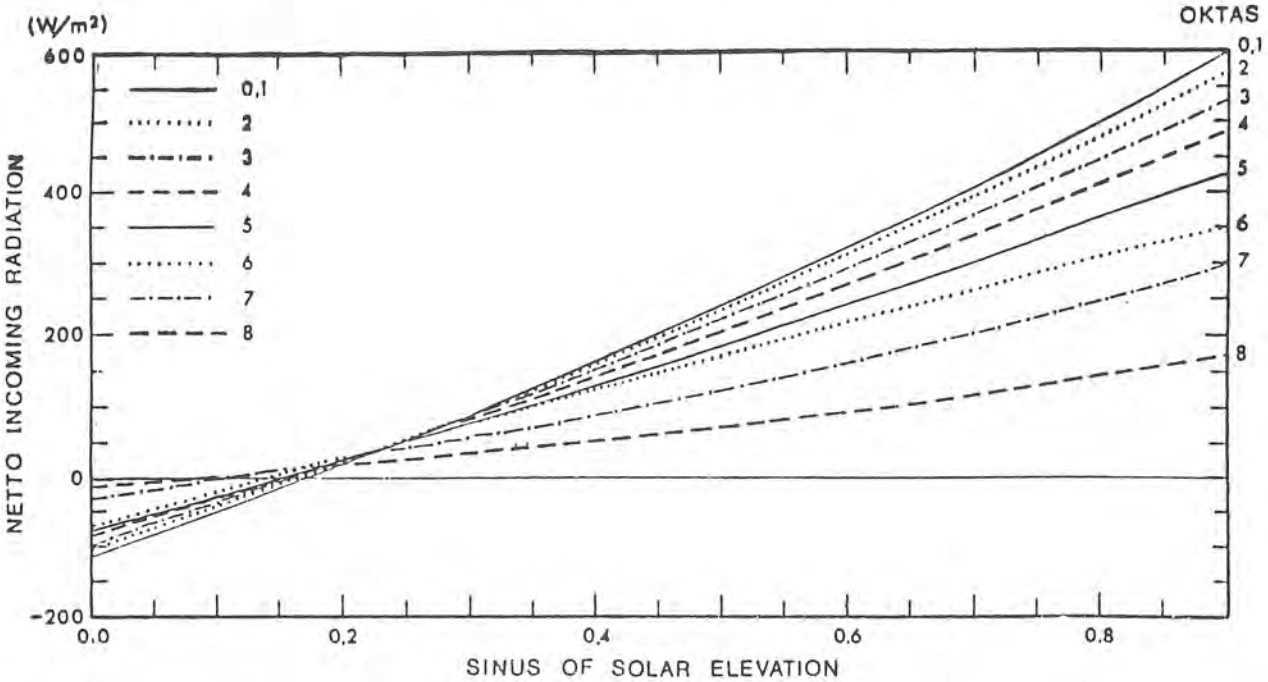


Figure 1. Net radiation as a function of 'effective' cloud amounts. From Nielsen et al 1981.

For the road stations we have local horizons given for 16 directions and we use these to reduce the net radiation by 25 % when the sun is below them. It is of course not realistic to reduce it 100 % since the sun still warms nearby surroundings as higer trees etc. The figure 25 % was found to give realistic effects for some test sites.

In the road surface model we have used the simple assumption that

$$G_0 = C \times R$$

This is a fair approximation and the proportionality constant C has been estimated as 0.19 for daytime (R>0) and 0.32 for nigthtime (R<0) (Nickerson and Smiley, 1975; Deardorff, 1978). For the roads and the winter season (the road services are run October-April) we used 0.25 and 0.40 respectively as it was found to give better results. This may be due to the fact that the evaporation is very small during the winter half year. Combining these two equations we see that the simple assumption says that the energy (R) is divided between ground heat flux and the turbulent fluxes in fixed ratios.

As we have no synoptic, advective effects included in the road system we just add synoptic changes as given by a weather model (LAM, SMHI) at the 850 hPa height. We have taken it from this level because we don't want to have the daily cycle from the LAM model interfering with this model.

In the objective system we have instead tried to make forecasted estimates of the turbulent fluxes using data from the lowest level (σ=0.992, about 64 m) in the weather model. This is a more physical approach to include synoptic scale changes and effects. We have then used similarity theory with

$$H = -\frac{(\Theta_{64} - \Theta_2) \times k \times u_* \times \varrho \times c_p}{\int_2^{64} \Phi_h dz}$$

$$u_* = -\frac{k \times u_{64}}{\int_{z_0}^{64} \Phi_m dz}$$

$$L=-\frac{\varrho\times c_p\times T\times u_*^3}{g\times k\times H}$$

where the empirical coefficients involved in Φ_m and Φ_h were chosen in accordance with measurements analysed by Dyer and Hicks (1970) and with modifications according to Högström (1988). The iterative scheme that must be used to derive the unknowns L(Monin-Obukhov length in Φ_h and Φ_m), u_* and H was adopted from Bergström (1986). The roughness length z_0 was taken as 1.0 for forests, 0.6 for urban areas, 0.1 for agricultural areas and 0.001 m for seas and lakes. Conventional notations are used and von Karman's constant k is set to 0.4.

Note that the temperature at 2 m is forecasted but is changed in the equation system (for H, u_* and L) only after the update time interval of 20 minutes in the flux calculations.

Because of the poor quality of specific humidity in the weather model, E was estimated from a Bowen ratio which was allowed ty vary around a climatological value using analysed ground moistures (made operationally at SMHI).

When G_0 then is derived as the net of the other terms in the energy balance equation it is not allowed to be too far from the simple estimate given by the proportionality relation. Thus we use formulae which modifies $G_0^{\prime}$ (here the value obtained from the proportionality relation) according to

$$G_0^{\prime\prime}=G_0^{\prime}-(G_0^{\prime}-G_0)^{0.7} \qquad if \;\; G_0\leq G_0^{\prime}$$
$$G_0^{\prime\prime}=G_0^{\prime}+(G_0-G_0^{\prime})^{0.7} \qquad if \;\; G_0\geq G_0^{\prime}$$

These restrictions were necessary because of the unrealistic values that now and then are obtained using similarity theory formulae on the sometimes quite crude input data from weather models. To summarize this section we can say that for many practical applications the proportionality relation offers a rapid short-cut to obtain reasonable ground heat fluxes while the flux calculations is a bit more satisfactory from a theoretical point of view. The latter formulation requires input from large scale weather models to give upper boundary conditions for this model.

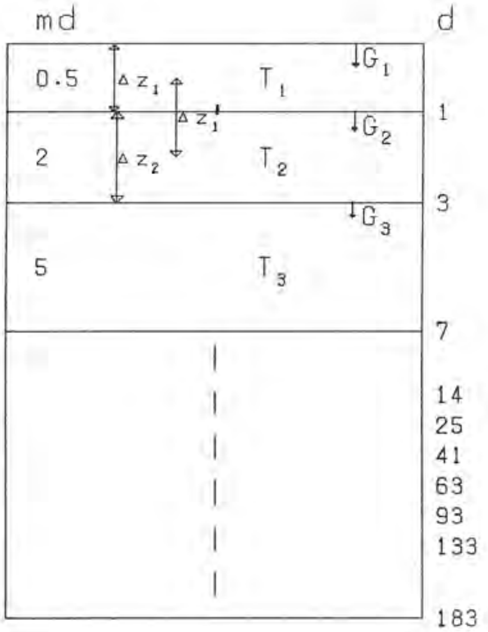
THE NUMERICAL MODEL OF THE GROUND - BOTH SYSTEMS

Within the ground the heat conduction and the evolution of the content of heat are solved in a two step iteration using

$$G_i = -\frac{K_i \times (T_{i+1} - T_i)}{\Delta z_i'}$$

$$T_i(t_0 + \Delta t) = T_i(t_0) - \frac{(G_i - G_{i-1}) \times \Delta t}{C_i \times \Delta z_i}$$

Notations and depths are given in Fig 2. We have used a time step in these calculations of 100 seconds. This short time step is necessary because of the thin upper layers of the ground. Note that the calculations of the net radiation and the ground heat flux G_0 are performed every 20 minutes.



K: heat conductivity (W/(m·K))
C: specific heat capacity (J/(m^3·K))
T: temperature (K)
G: soil heat flux (W/m^2)
md: mean depth (cm)
d: depth (cm)

Figure 2. Explanation of the notations used in the ground heat calculations.

Typical values on K and C for a road were obtained from the Road and Traffic Institute in Linköping (personal communication, Lars Stenberg) while the other values are interpolated from data in Wijk and Vries (1963) and Sellers (1975). All coefficients used are given in Table 1. When snow covers the ground snow depths are taken from the automatic, operational analysis at SMHI. For the roads no snow depths were used. For all soils a thin humus layer occupies the uppermost parts (see Table 1).

Table 1. Values on K ($W/(m\cdot K)$) and $C\cdot 10^{-6}$ ($J/(m_3\cdot K)$) at different depths.

0.5	2.0	5.0	11.5	19.5	34.5	52.0	78.0	113	158	mean deapth (cm)	
1.80	1.80	1.60	1.40	1.40	1.50	1.50	2.20	2.90	2.90	C*E-6	Road.
1.80	1.80	1.45	1.10	1.10	1.60	1.60	1.75	1.90	1.90	K	-"-
1.73	1.78	1.83	1.83	1.83	1.83	1.83	1.83	1.83	1.83	C*E-6	Dry moraine used
0.21	0.57	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	K	for dry forests.
2.87	2.64	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40	C*E-6	Wet moraine used
0.35	0.96	1.57	1.57	1.57	1.57	1.57	1.57	1.57	1.57	K	for wet forests
1.73	1.86	1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.98	C*E-6	Dry clay used for dry
0.21	0.45	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	K	agro and urban areas.
2.87	2.70	2.54	2.54	2.54	2.54	2.54	2.54	2.54	2.54	C*E-6	Wet clay used for wet
0.35	0.74	1.14	1.14	1.14	1.14	1.14	1.14	1.14	1.14	K	agro and urban areas.
0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	C*E-6	Snow of old type.
0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	K	- " -

TRUE SURFACE TEMPERATURE AND SCREEN AIR TEMPERATURE - BOTH SYSTEMS

The calculations accounted for gives a temperature that should be representative for the uppermost centimetre. Especially for an ideal surface the very surface temperature may be more extreme. Also the road sensors may lie both above or below a depth of 0.5 cm. Further there is always special local and often topographical effects that can not be taken into account by a one dimensional model. Therefore the road service stations are used to calibrate the model in a statistical and time adaptive way. If the measured and calculated temperature ranges of a 24 hour period are given by A_m and A_c respectively we obtain a ratio

$$A = \frac{A_m}{A_c}$$

With a previous estimate of A, A', a new value can be derived from

$$A'' = \nu \times A + (1-\nu) \times A'$$

Here we have used ν=0.1 to get a memory of the order 10 days. A'' is used to amplify the calculated changes and for most stations its value is above one which indicates that the road sensors lie very near the ground or that the sites are of extreme types typical of valleys with stronger than average nighttime inversions. Thus we take (with T_s' as the initial value of the ground sensor and T_1 and T_1' as the actual and initial temperature in the uppermost surface layer)

$$T_s = A'' \times (T_1 - T_1') + T_s'$$

When we cannot compare our forecasts with observations, as in the objective system, we have used the amplitudes 1.9 for forests and urban areas and 2.1 for agricultural areas. This will, hopefully, give surface temperatures that are representative for a very thin soil layer.

The forecasted screen air temperature at 2 metre (T_2) is obtained from a surface temperature by a relaxation formula (with T_2' as the previous value)

$$T_2 = T_2' + \alpha \times (T_s - T_2')$$

with α as 1/6 which gives an e-folding time of two hours as we have a time step of 20 minutes between successive estimates of T_s.

Note that in the UK model (Rayer, 1987; Thornes, 1989) the 2-metre temperature is given by the forecaster and is then used as an upper boundary value in the model formulation. This is a large difference from our system.

INITIAL VALUES - THE OBJECTIVE SYSTEM

In the road service system the forecasted soil profiles are saved and used at the next calculations. Also we have a measured soil temperature in the uppermost layer as a starting value.

The situation is more complicated when we have no soil temperature measurements and when the model is run now and then without access to an initial profile within the ground. Then we start with a 2-metre temperature and extrapolate down to the ground using wind and cloud information. The maximum difference (with different sign day and night) is allowed to be four degrees in cloudfree and near calm conditions. The extrapolation is a function of clouds, wind and sun elevation.

Within the ground a curve is constructed by using a climatological temperature at the bottom layer and this extrapolated surface temperature (at a depth of 0.5 cm). For two levels in between weighted means are calculated using the boundary values. A spline formula is then used to interpolate a continuous curve. The extrapolation formulae used here are, admittedly, quite subjective and not given in detail but a typical ground profile is given in Fig. 3.

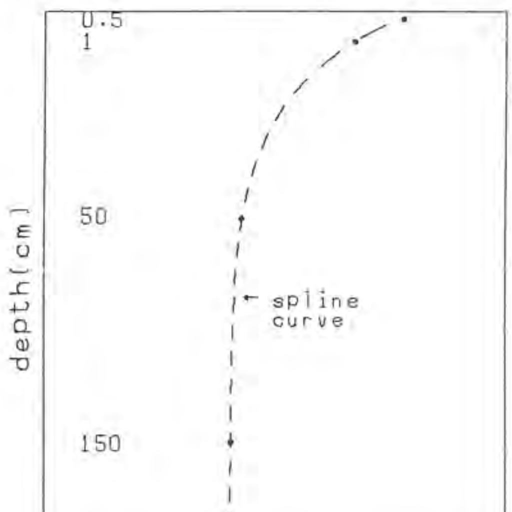


Figure 3. A sketch of the points used in the ground to derive an initial temperature profile.

It is quite important to get a reasonable initial profile in the ground. If we eg have a very shallow cold layer when we start our integration during a night it will be much easier to get a rapid warming after sunrise compared with an isothermal initial profile.

RESULTS FROM THE ROAD SERVICE SYSTEM

We have given figures from three periods for the road station Lövstad nearby Norrköping in Östergötland. These figures show typical improvements with this model compared with simple statistical extrapolations, a linear trend model and a persistency model.

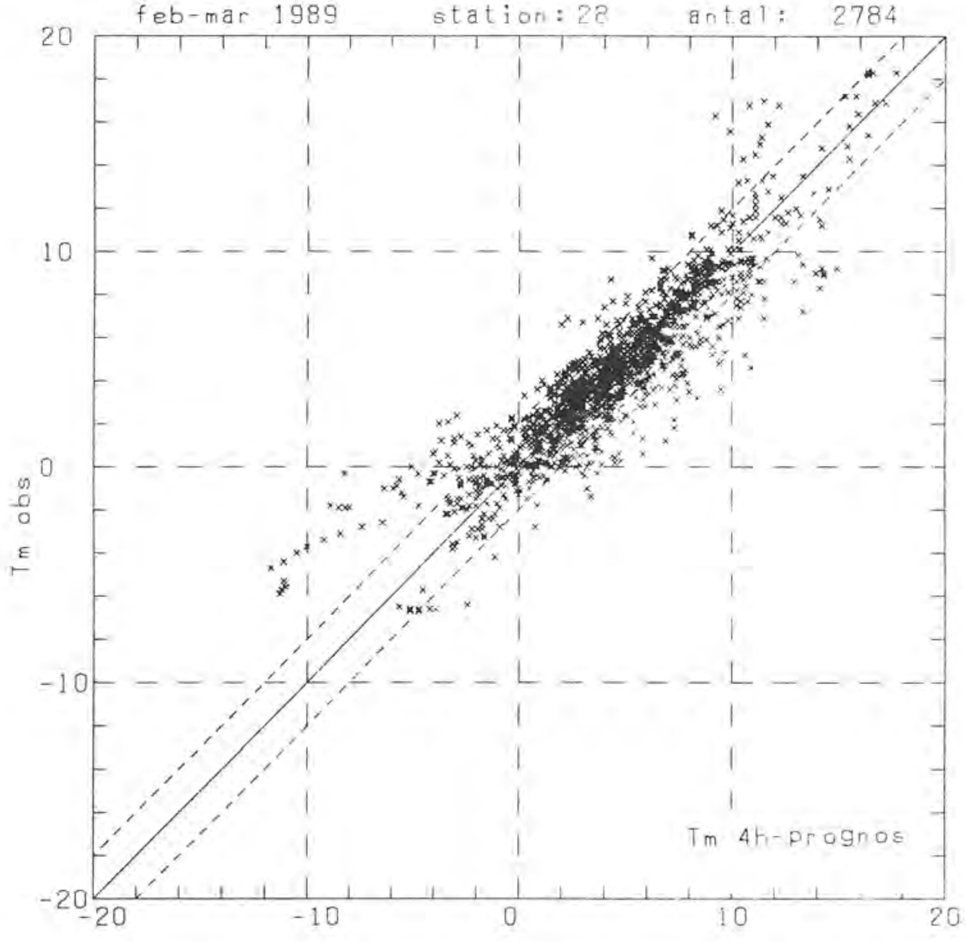


Figure 4a. Verification of four hour surface temperature forecasts for Lövstad, February-March 1989. The energy balance method.

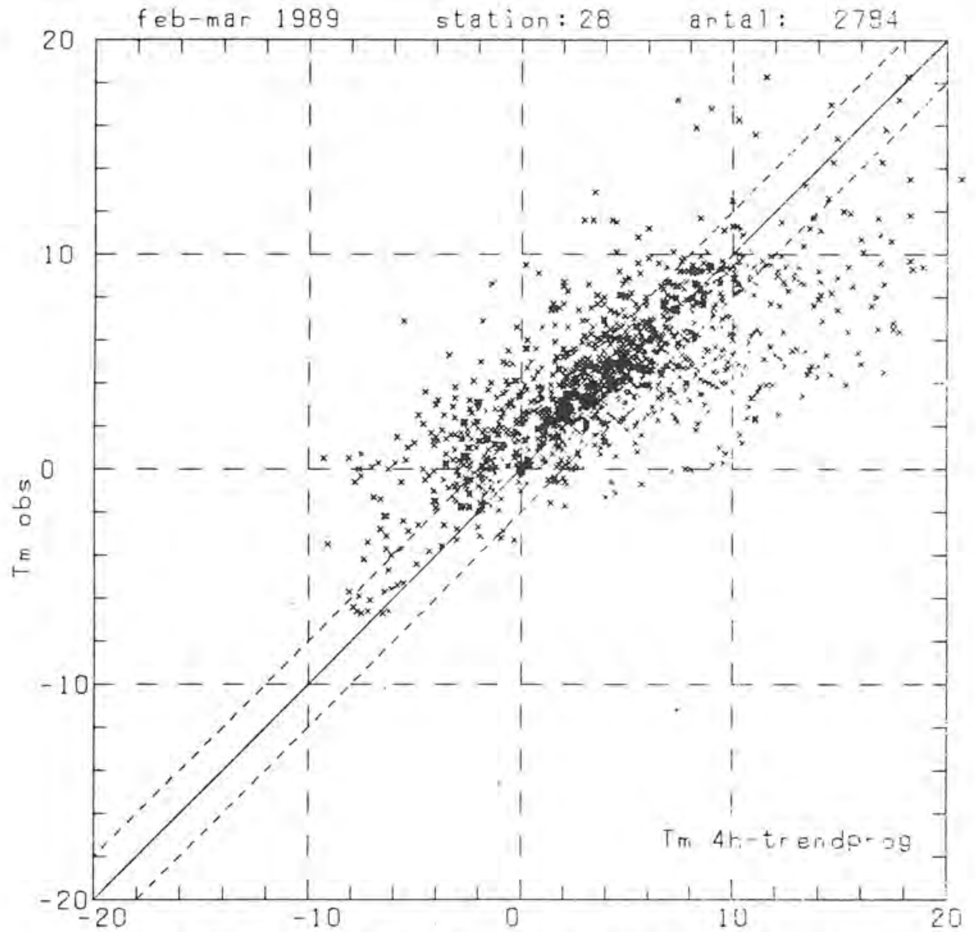


Figure 4b. Verification of four hour surface temperature forecasts for Lövstad, February-March 1989. The linear trend method.

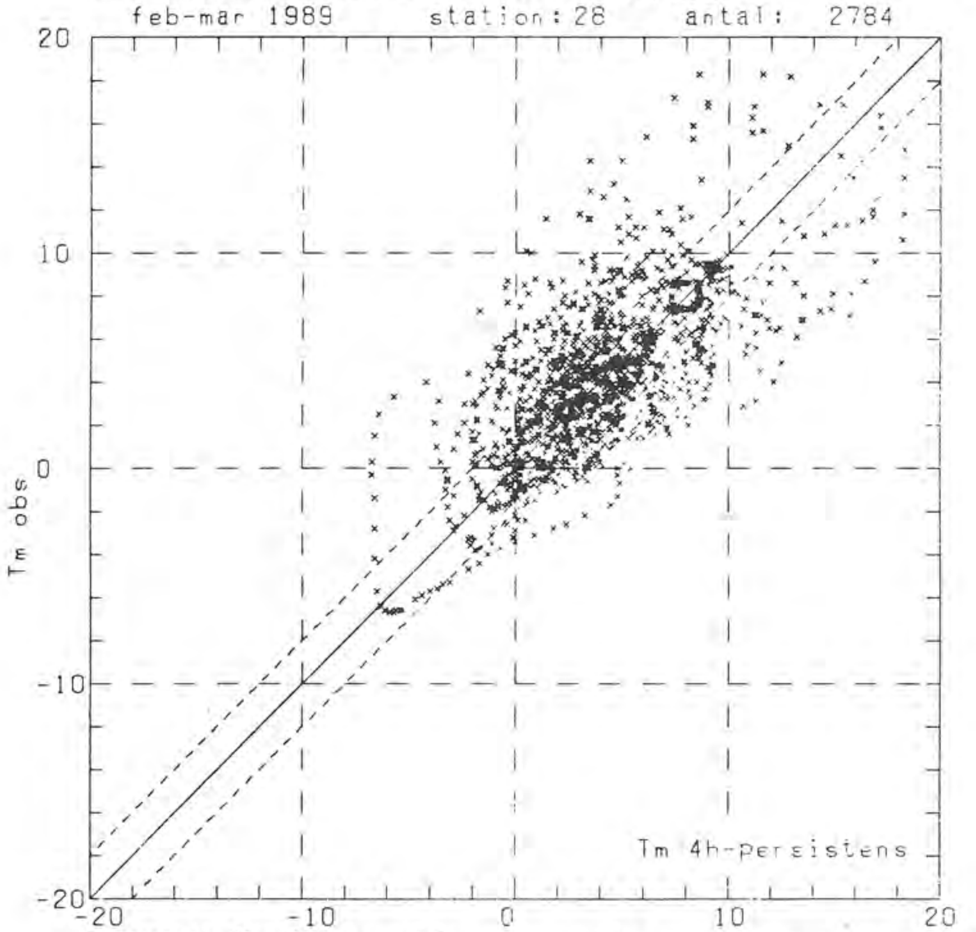


Figure 4c. Verification of four hour surface temperature forecasts for Lövstad, February-March 1989. The persistence method.

In the comparison for the 1989/90 season we used a daily variation persistency instead of a strict persistency. We then take the observation and add the difference observed between the forecast time and initial time from the preceding day. This will give good forecasts when the daily variation repeats itself. We can see that the mean absolute errors for the three methods were 1.19, 2.24 and 1.71°C for December 1989 and 1.29, 2.88 and 1.60°C for February at Lövstad for the energy balance model, the linear trend model and the daily variation persistency model respectively. The much colder month of the two was December 1989 but nevertheless it was the mild and windy February that was somewhat more difficult in forecasting, perhaps because of a larger number of traversing weather systems.

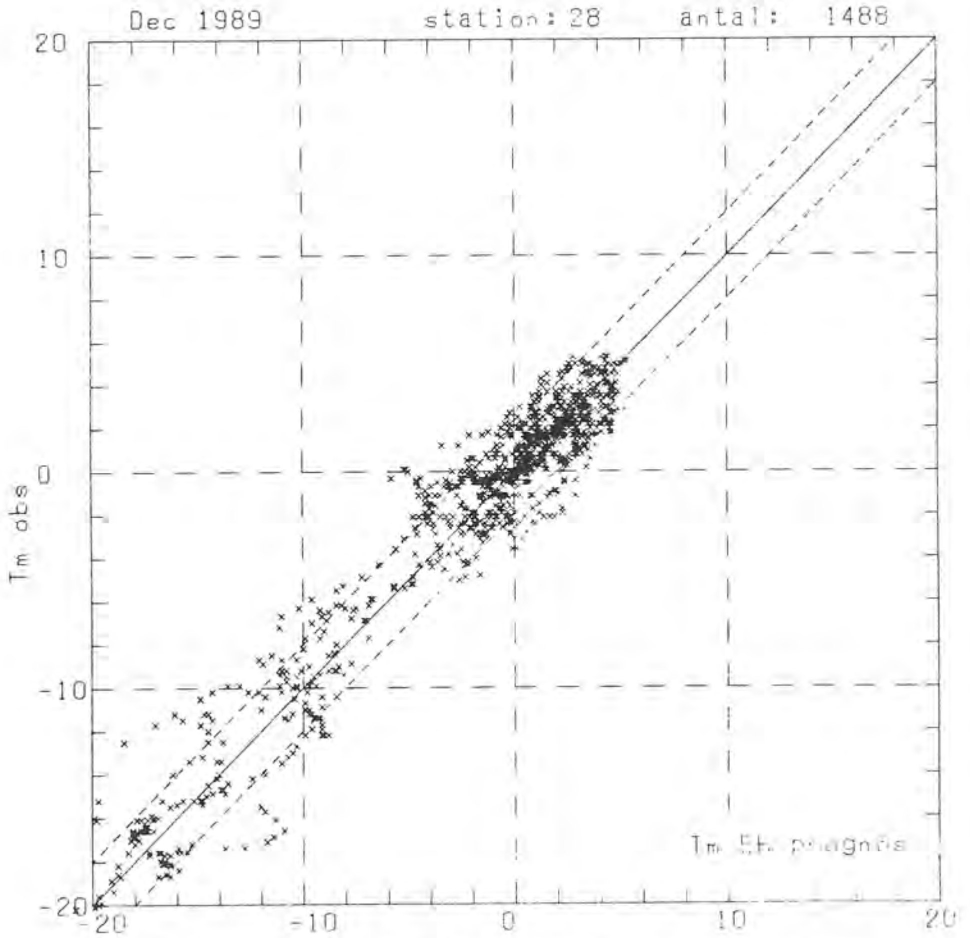


Figure 5a. Verification of five hour surface temperature forecasts for Lövstad, December 1989. The energy balance method. Mean absolute error 1.19°C.

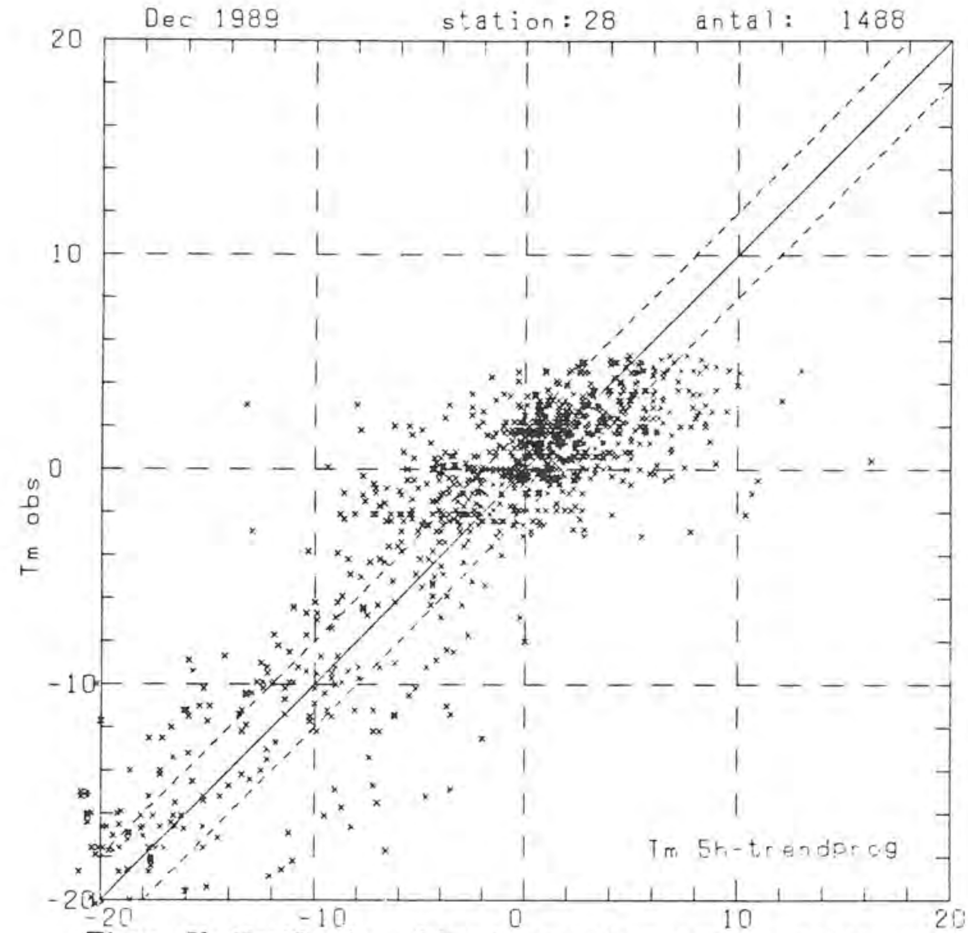


Figure 5b. Verification of five hour surface temperature forecasts for Lövstad, December 1989. The linear trend method. Mean absolute error 2.24°C.

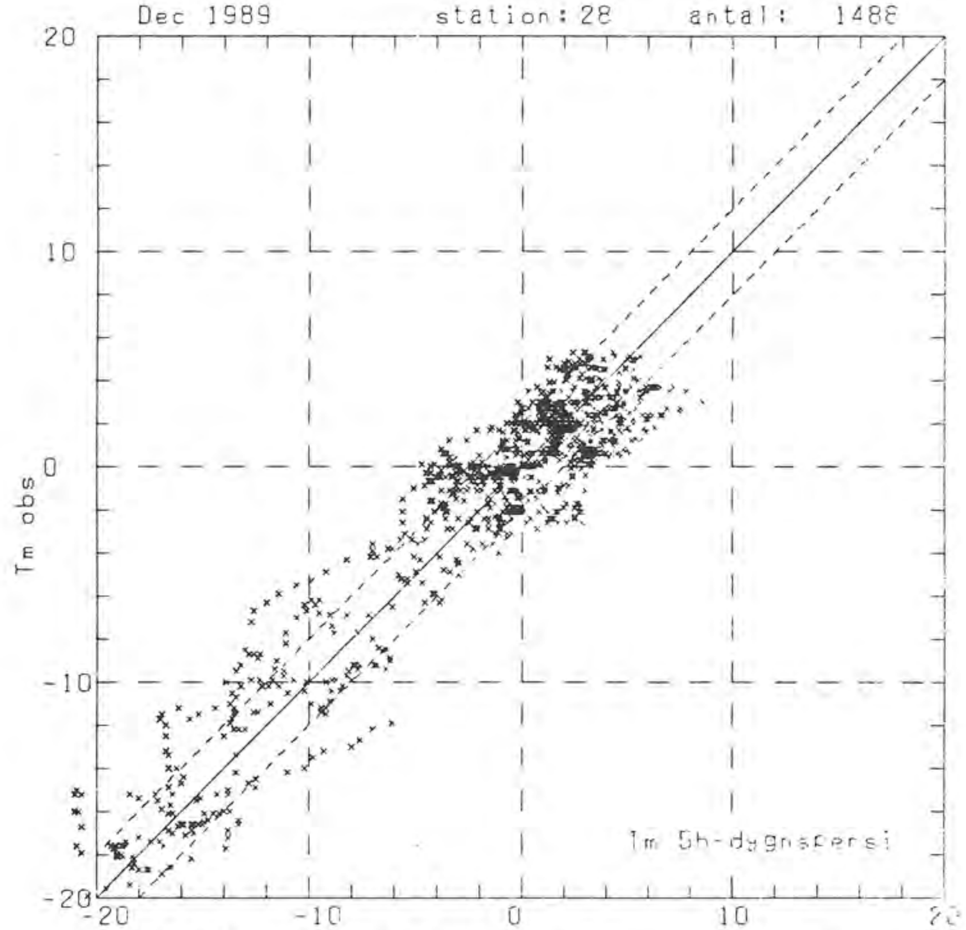


Figure 5c. Verification of five hour surface temperature forecasts for Lövstad, December 1989. The daily persist-ence method. Mean absolute error 1.71°C.

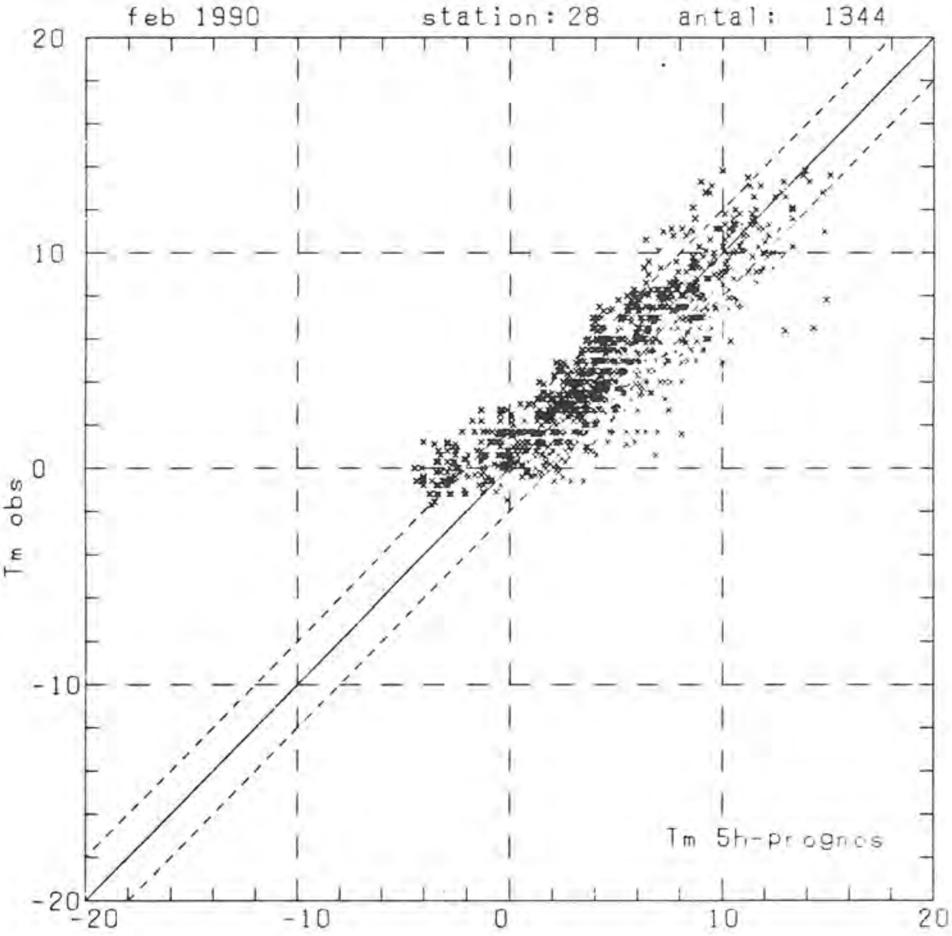


Figure 6a. Verification of five hour surface temperature forecasts for Lövstad, February 1990. The energy balance method. Mean absolute error 1.29°C.

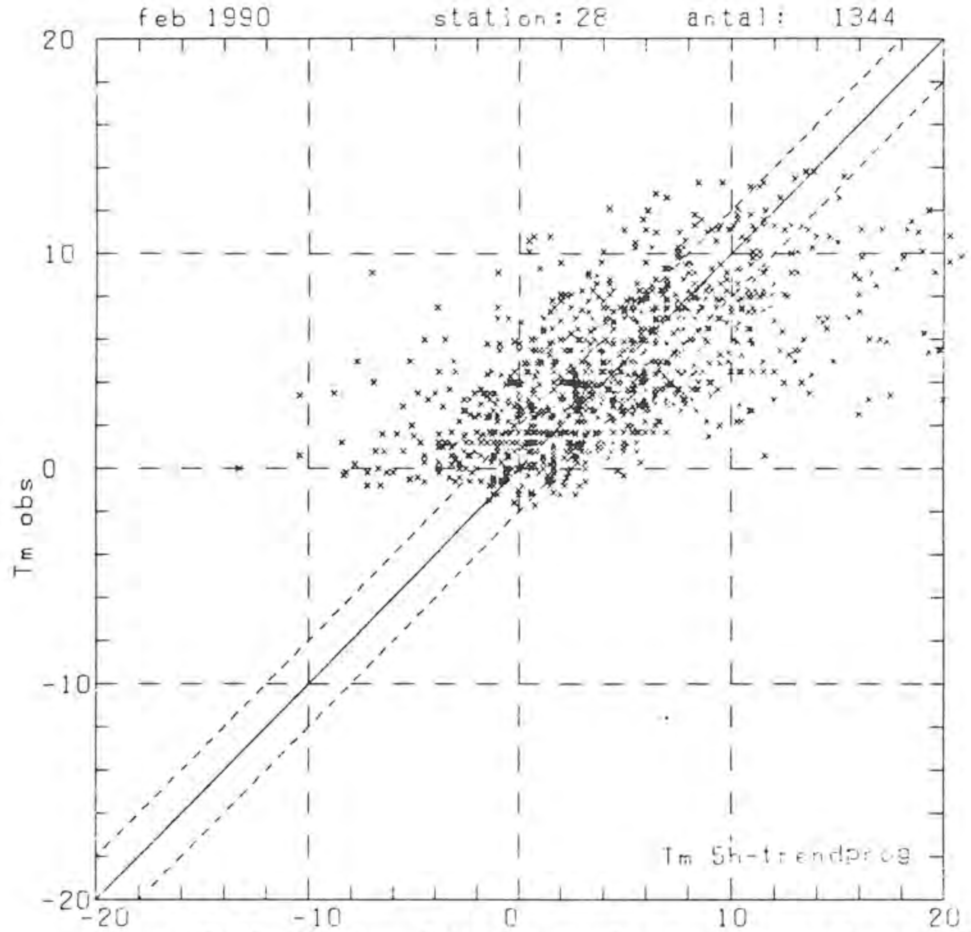


Figure 6b. Verification of five hour surface temperature forecasts for Lövstad, February 1990. The linear trend method. Mean absolute error 2.88°C.

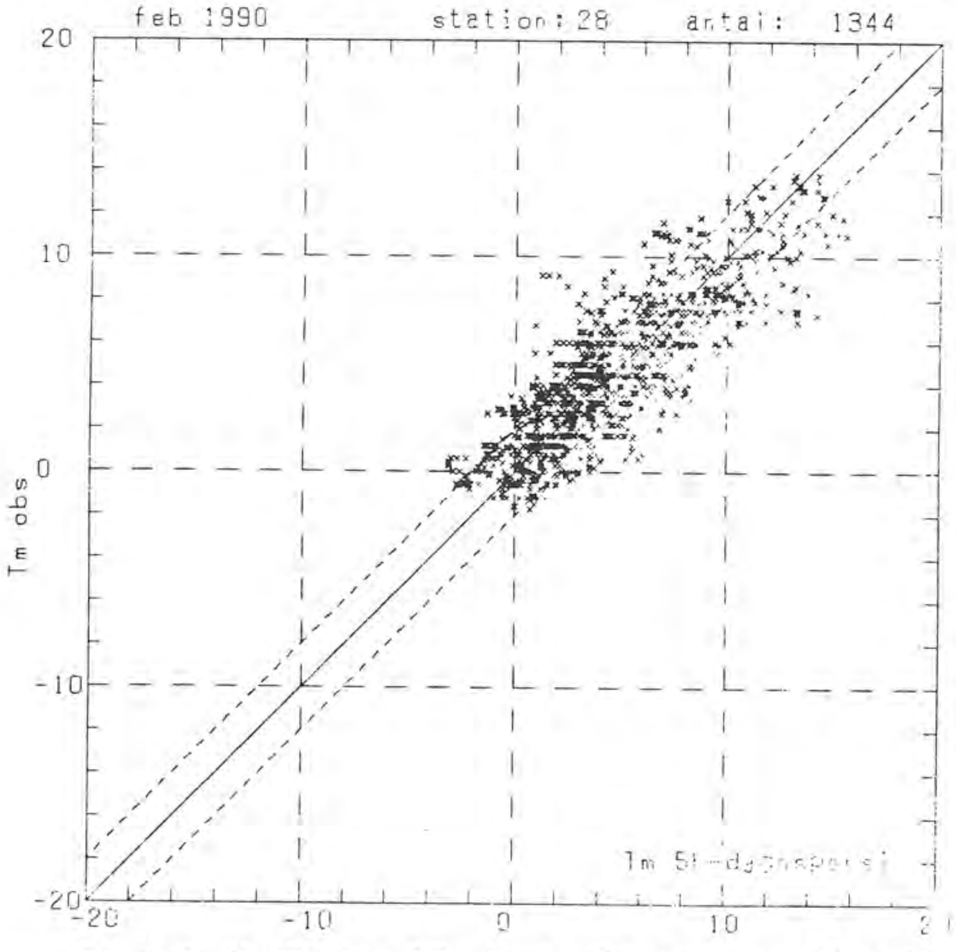


Figure 6c. Verification of five hour surface temperature forecasts for Lövstad, February 1990. The daily persistence method. Mean absolute error 1.60°C.

RESULTS FROM THE OBJECTIVE SYSTEM

The objective system can give temperatures for any points within the meso-beta grid or for the whole area. In figure 7 we show a map with forecasted 2-metre temperatures at 12 UTC 30 May 1990 and with 00 UTC the same day as starting time.

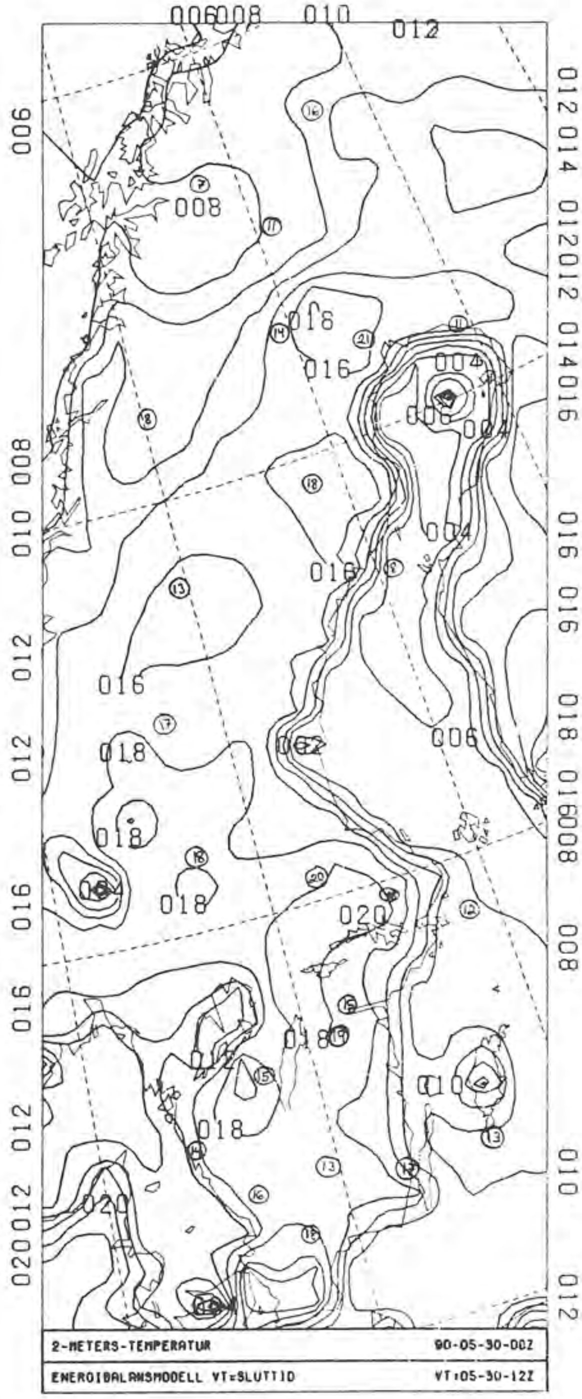


Figure 7. Twelve hours forecasted screen level temperatures from 00 to 12 UTC 30 May 1990. Within rings some typical observations are given.

Note that no forecasts are made for grid points over water where the the temperature is kept constant except for a synoptic change (SMHI-LAM 850 hPa). In this specific case with mainly clear weather the actual observations at 12 UTC were in good agreement with the forecasted temperatures except in the southernmost part where low clouds and showers reduced the temperatures some two to five degrees. As an example we find 13°C at Växjö where showers was observed while the forecast gives about 17°C.

During a few summer weeks 1990 we run the objective system for test purposes. Then we calculated mean error (me) and mean absolute error (mae) in °C for forecasts 00-12 UTC and for 12-24 UTC.

forecast	number	me	mae
00 to 12 UTC:	1620	-0.05	1.87
12 to 24 UTC:	4380	0.58	2.22

We can note a mean error (bias) for the forecasts valid at midnight. The mean absolute errors are of a typical magnitude reported in verifications of subjective forecasts.

DISCUSSION

The energy balance model described gives useful forecasts of surface temperatures and it can also be used, by a relaxation formula, to forecast air temperatures in the lowest part of the atmosphere. It has been shown that it gives substantially better forecasts than linear trend or daily variation persistency forecasts, although the latter model could be quite valuable if one has to use a pure statistical method.

A basic feature of the model is the estimation of the ground heat flux and we have found that it is hard to find better estimates than the simple proportionality model and the net radiation parameterization based mainly on cloud forecasts. These forecasts were given manually every second hour in the road service system. In a totally objective system they were taken from objective analyses and a limited area model.

The road service system is updated twice every hour and gives forecasts for surface temperatures and dew point temperatures (made in an analogous way but with much less amplitudes, A''). These forecasts have been integrated for five hours and a statistical technique has been used to correct the output in an adaptive manner. The meteorologist is incorporated by a frequent supply of cloud and wind forecasts. This is then a combined man-machine product with access to real time measurements.

The simple model described is well suited for personal computers although the input from large scale weather models must be solved differently or omitted. Hopefully we will find further applications like frost forecasts for farmers, temperature forecasts for runways and as a general tool for near surface temperatures at weather services.

APPENDIX A: AN ALTERNATIVE FORMULA – BOTH SYSTEMS

The simple proportionality relation

$$G_0 = \alpha \times R$$

can, alternatively but still very simple, be replaced by a formula that has some potential to take different evaporation conditions into account. Then we use the Bowen ratio defined by

$$B = \frac{H}{E}$$

and another parameterization of the ground heat flux, viz.

$$G_0 = \beta \times H$$

Then the energy balance relation can be rewritten as

$$H = \frac{R}{1 + \beta + 1/B}$$

Using the estimation procedure for the net radiation and with reasonable values on β and B we can get values on H and G_0.

The Bowen ratio varies during the year in a reasonably stable manner in our country. This is coupled to the evolution of the vegetation. Using curves in Sellers (1975) for outside of Copenhagen and Hamburg and making some smoothing we obtain the following values

Table 2. Mean Bowen ratios (Copenhagen and Hamburg).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
B	-1.8	-0.7	0.7	0.9	0.7	0.5	0.4	0.2	-0.2	-0.7	-1.8	-2.5

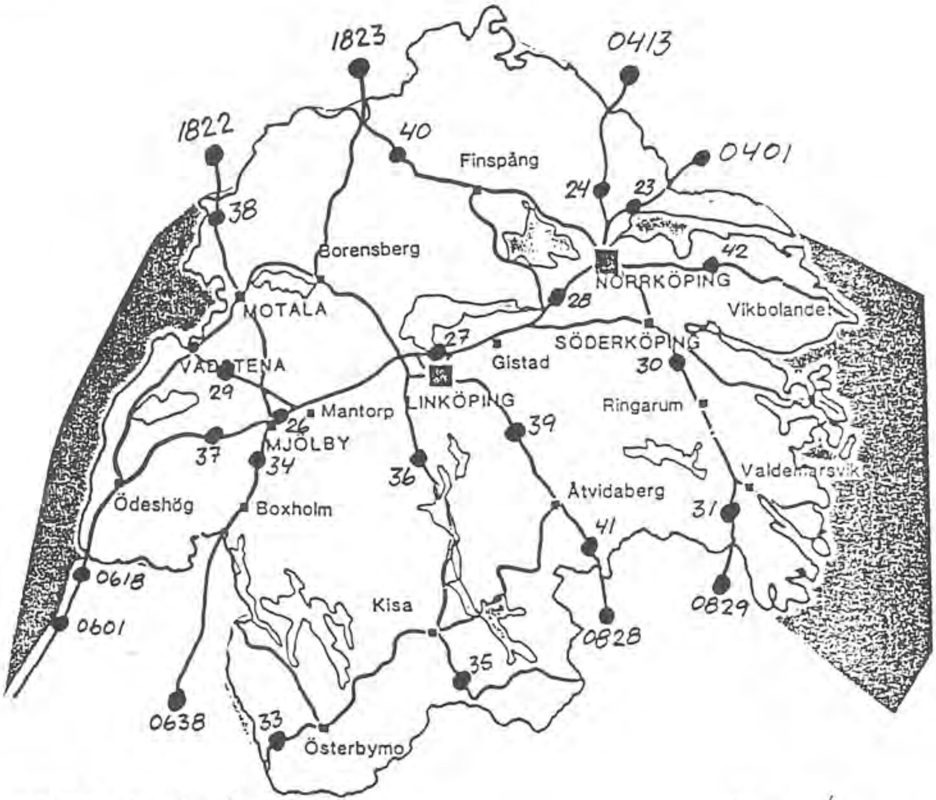
The values on the latent heat flux are quite near zero during September to February and 1/B should rather be set to zero for these months. Also there is a possibilty to adjust B a bit downwards just after rains and a bit upwards after prolonged drought spells.

The other coefficient, β, was estimated from measurements by Kasahara and Washington (1971) to 1/3. Deardorff (1978) found the two parameterizations of the ground heat flux about equally realistic.

The alternative way of estimating G_0 described here has been tested shortly in the objective system where, however, it is used only as a first guess, G_0' !

APPENDIX B: MAPS OF THE STATIONS - THE ROAD SERVICE SYSTEM

Two maps showing the VVIS-stations used in the road service system during the service season October 1990 - April 1991. VVIS= "Vägverkets Informationssytem".



0523 Kolmården
0524 Åby
0526 Mjölby
0527 Linköping
0528 Lövstad
0529 Vadstena
0530 Söderköping
0531 Valdemarsvik
0533 Rydsnäs
0534 Öringe
0535 Vadstugan
0536 Brokind
0537 Väderstad
0538 Medevi
0539 Bankekind
0540 Hållestad
0541 Gullebo
0542 Östra Husby

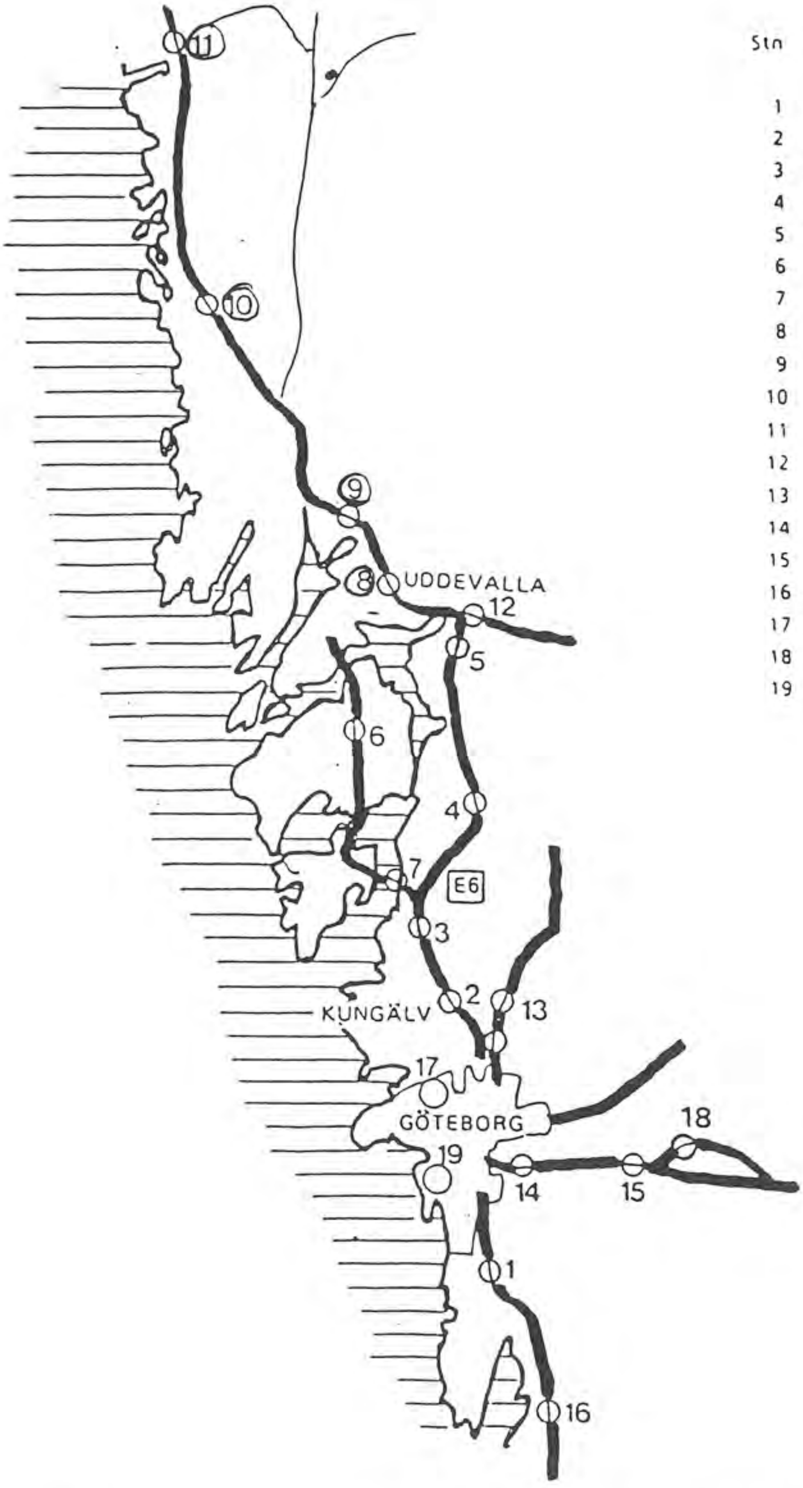
D-län
0401 Korsbäcken
0413 Västeråsen

F-län
0601 Gyllene Uttern
0618 Hägna
0638 Aneby

H-län
0828 Överum
0829 Västra Ed

T-län
1822 Brattebo
1823 Emma

Figure 8: A map with the VVIS-stations in "Östergötlands län" - and some surrounding sites - , 1990/91



Stn	Namn	Ao
1	Sandsjöbacka	
2	Kungälv	12
3	Jörlanda	12
4	Huveröd	13
5	Grohed	13
6	Kalseröd	14
7	Tjörnebron	12
8	Grytingen	21
9	Munkedal	21
10	Hud	23
11	Hogdal	24
12	Risån	13
13	Surte	P24
14	Delsjön	11
15	Kopparbo	11
16	Torpa	
17	Öxnäs	12
18	Rya	11
19	Fiskeback	

Figure 9: A map with the VVIS-stations in "Göteborgs and Bohus län" - and some neighbouring stations - , 1990/91

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